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REPORT

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PREDICTION OF IGNITION TRANSFER RELIABILITY IN PYROTECHNIC SYSTEMS USING THE VARICOMP TECHNIQUE

Leo de Yong

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The reliability of transfer of ignition between two elements in an explosive train is of paramount importance to proper functioning of a device. Prediction of this reliability is therefore necessary in designing ignition systems. To overcome testing prohibitively large numbers of samples, penalty testing was developed. The VARICOMP technique is one such penalty test developed for explosive trains. This report examines the theory of the VARICOMP technique and applies it to predicting ignition reliability in pyrotechnic trains.

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Prediction of ignition transfer reliability in pyrotechnic systems using the varicomp technique

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ABSTRACT

The reliability of transfer of ignition between two elements in an explosive train is of paramount importance to proper functioning of a device. Prediction of this reliability is therefore necessary in designing ignition systems. To overcome testing prohibitively large numbers of samples, penalty testing was developed. The VARICOMP technique is one such penalty test developed for explosive trains. This report examines the theory of the VARICOMP technique and applies it to predicting ignition reliability in pyrotechnic trains.

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CONTENTS

PREDICTION OF IGNITION TRANSFER RELIABILITY IN PYROTECHNIC SYSTEMS USING THE VARICOMP TECHNIQUE

1. INTRODUCTION

In the development of pyrotechnic trains which function by transfer of initiation from element to element, there is a need to predict the reliability of transfer when the train is in the armed configuration, and how resistant to transfer each element will be in the safe configuration.

This problem also exists in predicting the safety and/or reliability of detonation transfer in explosive trains. One solution is to manufacture and fire a large number of devices. However, the expense involved is prohibitive and the testing is time consuming. Alternative means have been to use penalty tests, where a barrier is inserted between the elements of the train, or the elements are misaligned. However, mechanical derangements of the system can make the data from the penalized system irrelevant to the tactical system. To overcome these problems, the Varicomp technique was developed [1]. It is a combined experimental and analytical method for predicting detonation transfer reliability or safety at a high level of confidence from limited direct experimental evidence.

In most pyrotechnic devices, transfer of energy between a donor and an acceptor can be assumed to occur via heat transfer across an interface, usually an air gap, a response being caused by an environment which can exist in various intensities or dosages and which can be measured. These assumptions underlay the basic theory of gap testing (penalty testing) as used in the Varicomp technique and it should therefore be possible to apply this technique to the examination of pyrotechnic ignition trains.

The objective of the work described in this report is to validate the use of this technique as a means of predicting the reliability of ignition transfer between an igniter and a pyrotechnic acceptor.

Providing the calibration of the design pyrotechnic and the Varicomp pyrotechnic is carried out accurately and there are no differences between the test hardware and the final design hardware, the advantage of the Varicomp technique is the small number of tests required to predict accurately the true value of the donor stimulus.

2. EXPERIMENTAL

2.1 Experimental Design

A Varicomp explosive system is made up of three basic elements:

1. a donor which is initiated externally and provides the stimulus to initiate the acceptor

2. an acceptor which is initiated by the donor

3. an interface (metallic membrane, plastic membrane, air gap etc) between the donor and acceptor.

In running an explosive reliability test, the design system is tested with the acceptor replaced by one or more Varicomp explosives of lesser but known shock sensitivity (alternatively, for safety testing the system can be tested with a donor made from a less powerful Varicomp explosive). The reliability of a detonation transfer is then measured by the ability of the donor to initiate the less sensitive acceptor or the less powerful donor to initiate the acceptor. These performance tests are carried out with minimum deviation from the design configuration in relation to both the interface and the surrounds. By knowing how reliable the system is under the adverse conditions of the performance tests, it is possible to estimate how much more reliable it would be under actual conditions.

Therefore, in conducting a Varicomp analysis, two separate tests must be conducted.

1. Calibration Tests: These define the sensitivity of both the design and Varicomp explosives in terms of donor stimulus to acceptor response.

2. Performance Tests: A limited number of tests using the design configuration with the Varicomp explosive from which reliability of the design explosive may be determined.

To examine the use of the Varicomp technique with pyrotechnic systems, two experiments were designed using a donor of known stimulus.

1. Using a single Varicomp pyrotechnic acceptor, performance tests were carried out to determine the donor stimulus.

2. Using multiple Varicomp pyrotechnics, performance tests were carried out to determine the donor stimulus.

The measured donor stimulus could then be compared to its known value, thus establishing whether the method would satisfactorily predict the reliability of ignition transfer between an igniter and a pyrotechnic acceptor.

2.2 Flash Tube Apparatus

Reliability testing is carried out with the donor pyrotechnic (igniter) separated by an air gap from the acceptor pyrotechnic using a Flash Tube apparatus (Figure 1). Here, the standoff distance between the donor and acceptor is analogous to the observed gap in the Small Scale Gap Test used for calibrating explosives [2].

The flash tube consisted of a vented 13 mm ID cylindrical brass tube into which a pellet of pressed pyrotechnic was placed. The pellet was made by pressing 1.0 g of composition into a 12.6 mm diameter aluminium foil sleeve at 900 kg dead load. The standoff distance between the igniter and the pellet was varied by altering the lengths of the insert. A Bruceton statistical analysis [3,4,5] was carried out on the results to determine the 50% fire/no fire standoff distance ($\bar{D}$) and variance (σ^2_R).

2.3 Materials

The donor used was an M42F1 gasless percussion primer [6] and the pyrotechnic acceptor compositions were as detailed below:

Composition 1	$B/Pb_3O_4/Cr_2O_3$	(10:70:20)
Composition 2	B/Pb_3O_4	(10:90)
Composition 3	$B/Pb_3O_4/Cr_2O_3$	(10:60:30)
Composition 5	B/CuO	(15:85)

3. MATHEMATICAL BASIS AND STATISTICAL METHODS

Detailed statistical analysis is given in many references [1,2,7,8] however, a brief outline is given here.

3.1 Calibration of Design and Varicomp Pyrotechnics

(1) In explosive systems, a Small Scale Gap Test (SSGT) is conducted using a Bruceton test plan [3,4,5] to determine the gap between the donor and acceptor for 50% probability of acceptor response. It is important for the

estimation of large and small percentage points that the gap values be normally distributed. In most explosives systems, it has been found that the log of the gap is normally distributed. Therefore, to determine the donor stimulus corresponding to a measured gap, the following relationship has been used [2]:

$$X = A + 10\ B\ \log\left(\frac{GR}{GT}\right) \tag{1}$$

X	=	Donor stimulus (decibangs)
$\frac{GR}{GT}$	=	Ratio of Reference gap to Observed gap.
A,B	=	Arbitrary constants

For the data from the pyrotechnic flash tube, it was found that normalization was achieved by a direct linear relationship, ie stimulus directly proportional to standoff distance. A suitable relationship was found to be:

$$X = A - \frac{D}{B} \tag{2}$$

X	=	Donor stimulus (arbitrary units)
D	=	Standoff distance (mm)
B	=	Reference distance (mm)
A	=	Constant (arbitrary units)

(2) Knowing the stimulus required for 50% response, the stimulus required for the other percentage responses is determined using either a Logistic or Gaussian distribution function [3,7,9] depending on which is more appropriate.

Calibration of explosives uses the Logistic distribution due to its being proved more appropriate than the Gaussian. However, since no such data exist for pyrotechnics, a Gaussian distribution has been assumed.

$$Z = \frac{D - \bar{D}}{\sigma_R} \tag{3}$$

where	Z	=	standard normal variable or response (normits)
	D	=	value of standoff distance (mm) corresponding to observed percentage response P
	$\bar{D}$	=	mean value of standoff distance (mm)
	σ_R	=	standard deviation of the standoff distance (mm)

(3) In order to determine the one sided reliability limits of D at a confidence level C_c, the following equation is used [3,7]:

$$_{L,U}D = D \pm t_1 \sqrt{\left(\sigma_{\overline{D}}^{\,2} + t_2^{\,2}\,\sigma_\sigma^{\,2}\right)} \tag{4}$$

where $_LD$ = lower limit of standoff distance (mm)

$_UD$ = upper limit of standoff distance (mm)

t_1 = student t at confidence C_c

$\sigma_{\overline{D}}^{\,2}$ = variance of the mean standoff distance (mm)

t_2 = student t at percentage response P

$\sigma_\sigma^{\,2}$ = variance of the standard deviation of the standoff distance

This technique allows calibration graphs to be constructed as shown in Figure 2.

3.2 Performance Tests

Having carried out the calibration, a small number of Performance tests are conducted using the Varicomp pyrotechnic. The design pyrotechnic safety/reliability is then estimated from these results.

4. RESULTS

4.1 Bruceton Analysis

The results of the Bruceton staircase testing of the four pyrotechnic compositions, as well as the statistically derived data are shown in Table 1.

4.2 Calibration

As noted earlier, for the flash tube using pyrotechnics, a suitable relationship between donor stimulus and standoff distance is

$$X = A - \frac{D}{B} \tag{2}$$

Using the data in Table 1, and equation 2, values of A = 10 and B = 100 mm were found to be convenient for the analysis.

Using this, calibration curves for the pyrotechnic compositions were derived as shown in Figures 3 and 4.

4.3 Single Varicomp Pyrotechnic Analysis

Using the experimental results given in Table 1, calibration graphs were drawn for the design pyrotechnic (composition 1) and the Varicomp pyrotechnic (composition 5) along with the lower limit of reliability of the design pyrotechnic (Figure 3). Performance tests carried out using Composition 5 at a standoff distance of 250 mm (X = 7.5) showed 10 fires from 15 tests (67% response). Intersection of the 67% response line ($_OR_5$) in Figure 3 with the calibration line for composition 5 (Point M) yields an observed stimulus, $_OX$, of 7.6. The lower one sided 95% confidence limit (C_P) for the response (10/15 fires) of composition 5, $_LR_5$, is 42.2% [10]. The intersection of the 42.2% line with the calibration line of composition 5 (Point L) yields a lower stimulus value, $_LX$, of 7.4. As shown in Figure 3, points $_LX$ and $_OX$ yield the predictions of 99% (Point Q) and 82% (Point N) for the expected reliability and its lower limit, at greater than 90% confidence, for composition 1 as the design acceptor pyrotechnic with an M42F1 igniter and an air gap of 250 mm.

4.4 Multiple Varicomp Pyrotechnics Analysis

Using the data from Table 1, calibration graphs were drawn for the design pyrotechnic (Composition 1) and the three Varicomp pyrotechnics (Compositions 2, 3 & 5) along with the lower limit of reliability of the design pyrotechnic. Performance tests were carried out at a standoff distance of 260 mm (X = 7.4) with the following results:

Composition Number	Number of Tests	Number of Fires	Response (%)
2	10	9	90
3	7	6	86
5	5	2	40

Using these results, analysis was carried out as shown in Figure 4.

The intersections of the percentage response lines ($_OR_2$, $_OR_3$, $_OR_5$) with their corresponding calibration lines (Points J, K & L) yield the values of the observed stimuli ($_OX_2$, $_OX_3$, $_OX_5$) of 7.32, 7.36 and 7.54 respectively. Using the probit technique to calculate weighting factors [1,10] the weighted average stimulus was determined:

Composition	N	Response (%)	Response (Normits) [10]	Response (Probits) [10]	Stimulus (X)	Weighting Factor (W)	NW	NWX
2	10	90	1.275	6.275	7.32	0.336	3.36	24.60
3	7	86	1.050	6.050	7.35	0.439	3.07	22.60
5	5	40	-0.250	4.750	7.54	0.620	3.10	23.37

Σ NWX = 70.57

Σ NW = 9.53

Weighted average stimulus = $\frac{\Sigma \text{ NWX}}{\Sigma \text{ NW}}$ = 7.41

The intersection of the line corresponding to this value of stimulus ($_o\bar{X}$) and the calibration line for composition 1, yields an observed reliability of 97%. The intersection of $_o\bar{X}$ with the one sided lower limit of reliability for composition 1 (Point N), yields a lower limit of reliability ($_LR_1$) of 81%.

Therefore, the design acceptor pyrotechnic (Composition 1) with an M42F1 igniter and an air gap of 260mm would have an ignition reliability of 97% with a lower limit of 81%.

5. DISCUSSION

The 15 performance tests with the single Varicomp pyrotechnic analysis gave an igniter stimulus of between 7.4 and 7.6 (at 95% confidence) for a known stimulus of 7.5. The 22 tests conducted with three Varicomp pyrotechnics gave a weighted average stimulus of 7.41 for a known stimulus of 7.40. Thus, the modified Varicomp technique can readily be used with small samples to determine ignition reliability of pyrotechnic trains with little direct experimentation. However, care must be exercised in the use of this technique as there are a number of limitations and correct decisions which need to be made with respect to experimental design and procedure.

In the original Varicomp theory, calibration of the explosives was carried out using the Small Scale Gap Test [2] and many hundreds of experiments at various representative gaps. This allowed a very accurate response vs stimulus calibration curve to be obtained. In our modified technique, however, a simple 25-30 shot Bruceton analysis has been used to determine the 50% fire/no fire point which has been extrapolated to other percentage responses using Equation 3. This has the advantage of making the technique fast and inexpensive (in terms of material and time) whilst decreasing its accuracy and precision. The decrease in accuracy is due to distortion of the tails of the distribution extrapolated from the Bruceton 50% point whereas the decrease in precision is related to the number of trials - the gain in precision is proportional to the square of the number of trials.

Extrapolation of performance test data (for reliability) to the design pyrotechnic will be more accurate when the calibration of the design pyrotechnic is extended not from 50% response data but from 90% response data. However, if safety and reliability estimates are to be derived using the same calibration data, extrapolation from 50% data is more efficient in terms of time and effort.

However, our results show that the use of the Bruceton calibration technique will provide a useful prediction of the igniter stimulus. If the experimenter wishes to improve accuracy at the tails of the distribution then a series of Run-down tests can be performed or the Robbins Monroe technique may be used [12,13]. If he wishes to improve precision then the number of tests can be increased.

The choice of hardware in running a Varicomp test is also crucial to the validity of the results. Ideally, the calibration test method should match the performance test method as well as the final weapon configuration - in practice however this is rarely the case. The flash tube was chosen as the test apparatus because of its similarity in principle to most pyrotechnic ignition systems. However, there will be instances when the differences between the design ignition system and the test system will be so great, that the calibration data may be irrelevant. Then, a mock-up calibration test is required.

In many cases, the physical factors of the hardware may not match the calibration hardware. Williams [11] has shown that for flash tube diameters of 0.6 mm to 2.5 mm the standoff distance above which ignition transfer does not occur can vary by up to 100% depending on the flash tube diameter. He has also shown that this critical length varies with pellet pressing load. Similar results for explosive diameter and stimulus have been observed by Stresau and Means [8]. This behaviour highlights one of the Varicomp assumptions - the hardware simulation should be identical or nearly identical to the actual design hardware.

Clearly, there are few hard and fast rules for design of a Varicomp test and the experience of the experimenter is drawn on heavily in the design of the experiment.

6. CONCLUSION

This study shows that a modified Varicomp technique can be used in conjunction with small sample theory to predict the available stimulus from an igniter in a pyrotechnic system and the ignition reliability of the acceptor pyrotechnic. The use of the Bruceton calibration technique can provide adequate precision and makes elaborate and expensive calibration experiments unnecessary. However, for reliable predictions to be obtained, care must be taken to design the experiment to simulate the actual design hardware as closely as possible.

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TABLE 1

Bruceton analysis of pyrotechnic compositions
(N.B. 'D' denotes 'Stand off Distance')

Composition 1

D(mm)	Result																							
250														F										
300							F				F		N		F				F					
350		F				N		F		N		N				F		N		F		F		F
400	N		F		N				N								N				N		N	
450				N																				

$\bar{D}$ = 354.2

σ_R = 50.0

Composition 2

D(mm)	Result																									
280			F		F		F																			
310		N		N		N		F		F		F		F		F										F
340	N								N		N		N		N		F				F				N	
370																		F		N		F		N		
400																			N				N			

$\bar{D}$ = 331.9

σ_R = 49.8

Composition 3

D(mm)	Result																										
230	F										F				F												
270		F				F				N		F		N		F										F	
310			F		N		F		N				N				F		F				F		N		F
340				N				N										N		F		N		N			
370																					N						

$\bar{D}$ = 305.0

σ_R = 39.8

Composition 5

D(mm)	Result																												
220																			F		F		F						F
240								F				F						N		N		N		F				N	
260			F				N		F		N		F		F		N								F		N		
280		N		F		N				N				N		N										N			
300	N				N																								

$\bar{D}$ = 254.6

σ_R = 33.2

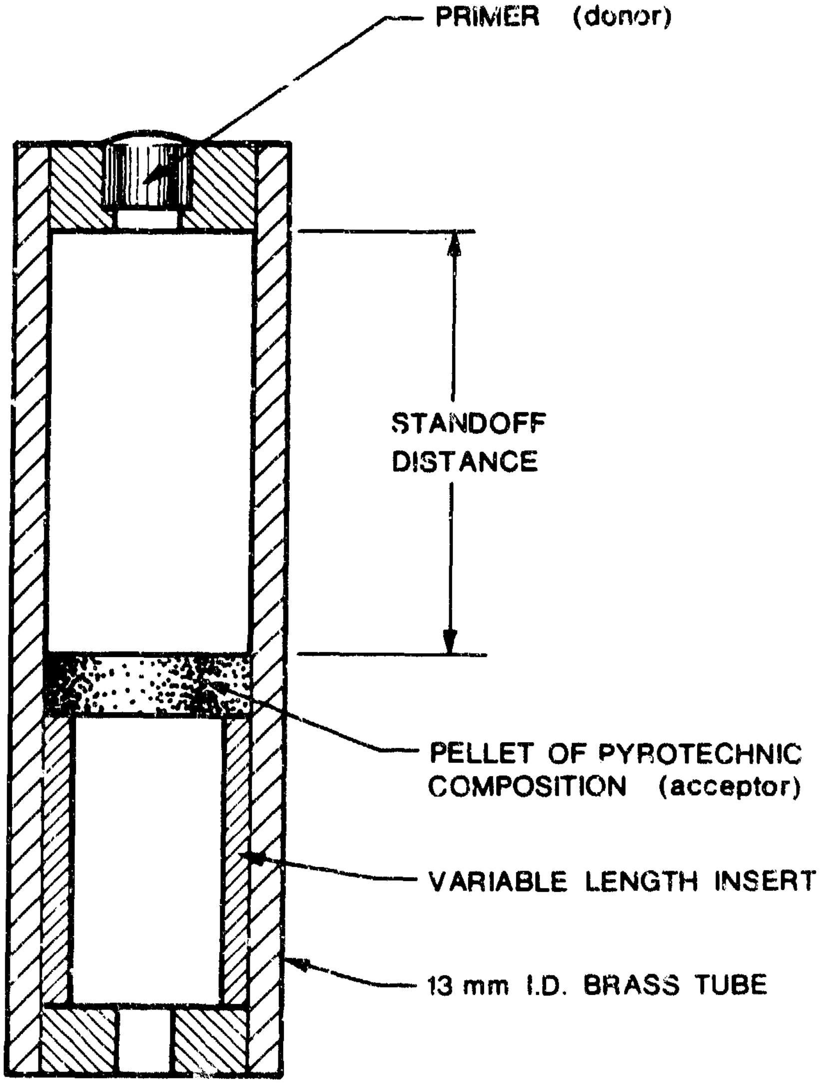

FIGURE 1 Flash tube for ignition transfer determination

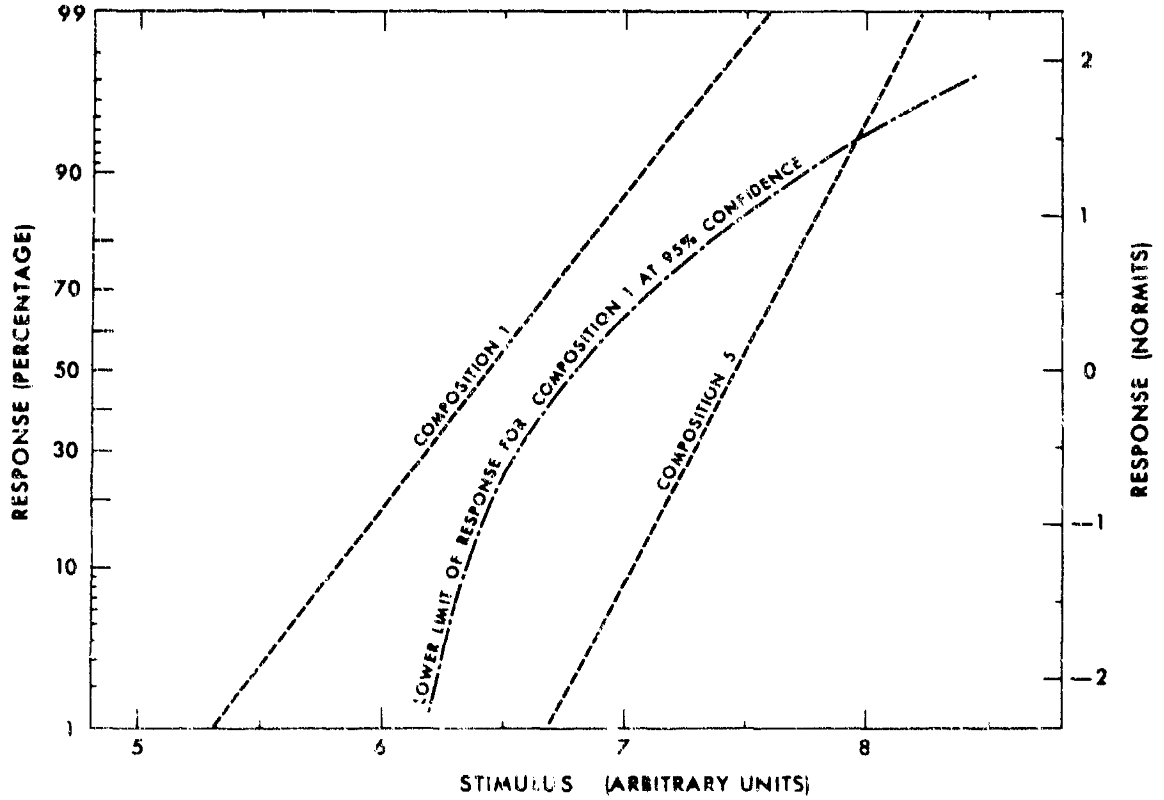

FIGURE 2 Calibration curves for design and Varicomp pyrotechnics including lower limit of response for design pyrotechnic

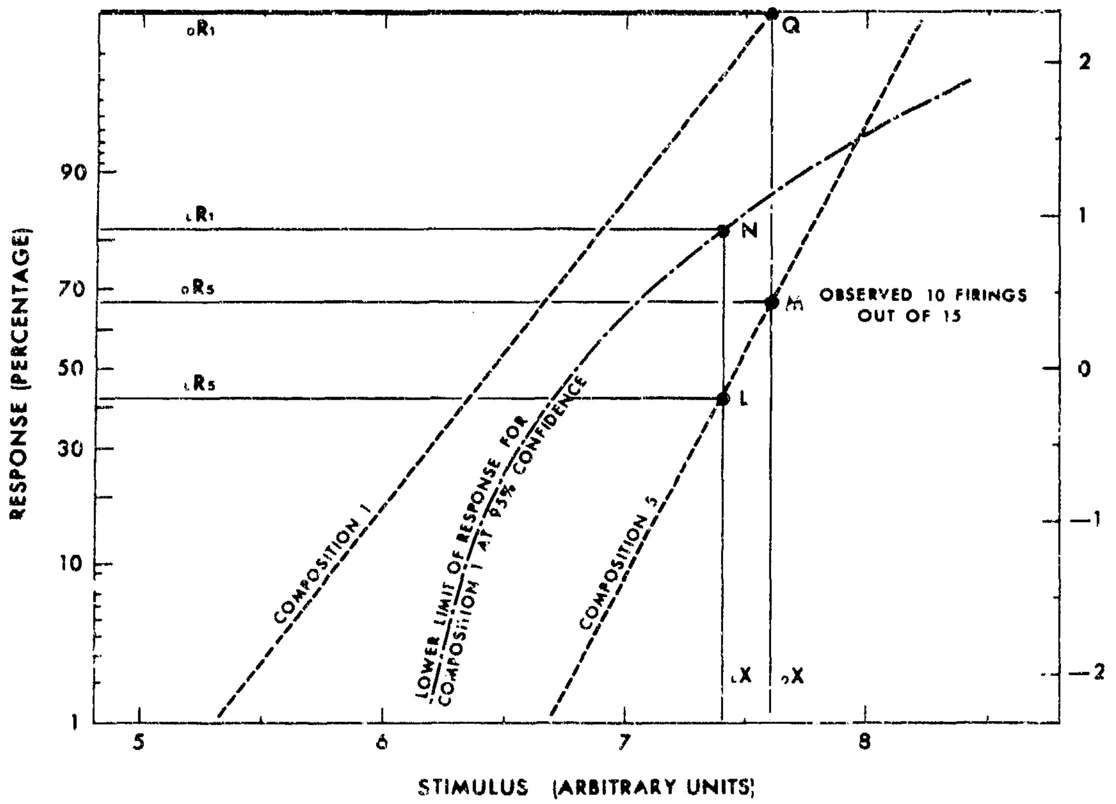

FIGURE 3 Reliability analysis using single Varicomp pyrotechnic

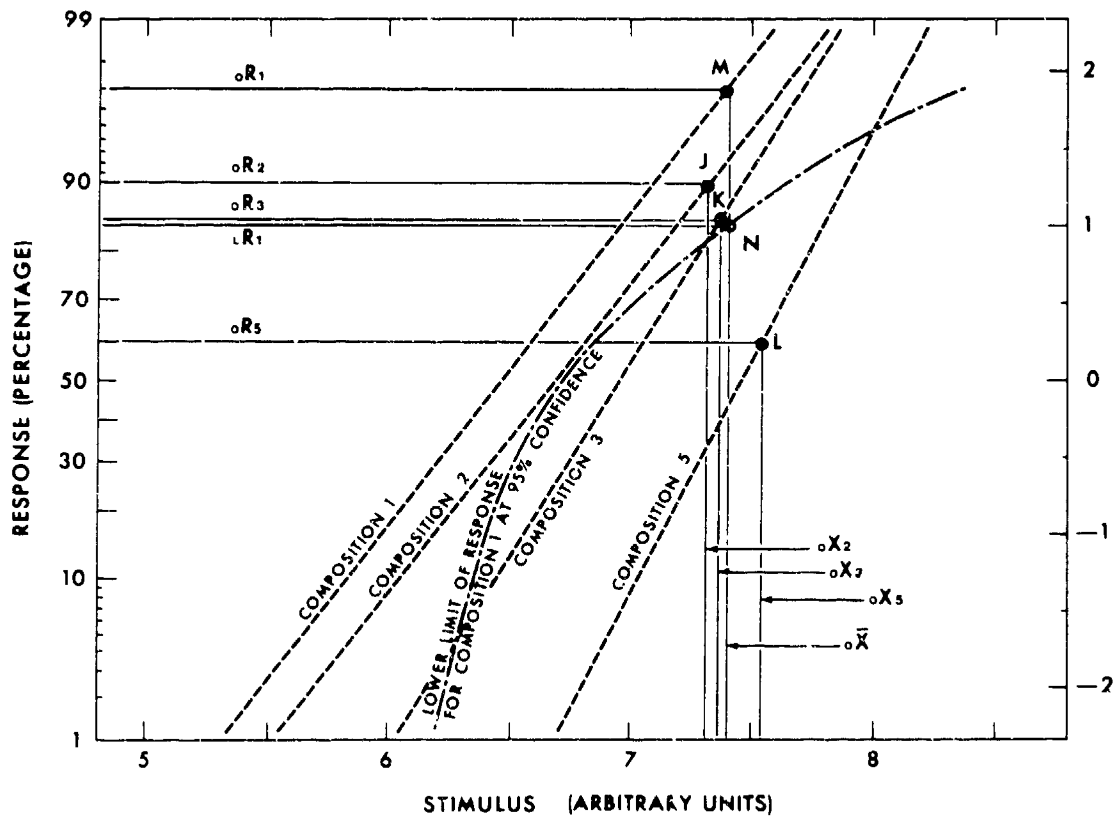

FIGURE 4 Reliability analysis using multiple Varicomp pyrotechnics